Calibration Attitude Maneuvers for the EOS AM-1 Platform: Engineering and Thermal Feasibility and Limitations, and Science Benefits

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I. Background Information on CAMs

One goal of the Earth Observing System (EOS) program is to make comparative measurements over many years from Earth-orbiting spacecraft to detect changes in terrestrial parameters, particularly climatic changes. To accomplish this and other goals, the calibration of the various remote-sensing flight instruments must be known over this entire time period to within a few percent, from the visible through the infrared. To this end, several investigators have instruments which carry their own on-board calibration devices, while others plan to view known sites or to view active field campaign sites after launch. Still others plan to depend on the intrinsic stability of their instrument, combined with consistency checks between channels and detectors. None of these techniques appear to have the potential for satisfying the requirement of knowing the characteristics of the instruments to better than a few percent over several years, especially when measurement continuity, combined with expected satellite lifetimes, requires that the instruments be on different platforms.

A possible solution to this problem has been discussed for some time within the EOS AM-1 platform community: performing spacecraft calibration attitude maneuvers (CAMs) to allow the instruments to view the Moon and/or cold space. The Moon provides a radiance target whose properties are essentially invariant over time, while cold space provides a zero level reference for detectors and electronics. One purpose of this white paper is to explore the CAM options from the perspective of quantifying potential gains in understanding the calibration/characterization of the AM-1 instruments. A second purpose of this white paper is to evaluate possible negative effects on the spacecraft and instruments resulting from stressing the spacecraft attitude control system and from modifying the instrument thermal environment.

II. Description of the Baseline CAM

The baseline CAM is designed to satisfy as many observational goals as possible while meeting all operational constraints. The goals include the following:

- a lunar nadir view,

- a clear view of deep space across the full scan region for all instruments,

motion across the Moon providing sufficient oversampling,
- a view of the Moon at minimum lunar phase (ie. greater than but not less than about 4 degrees).

There are a number of operational constraints placed on the baseline CAM and CAMs in general. The CAM must conform to the following constraints:

- the propulsion/thrust system must not be used (i.e. the turn rates and accelerations must be within the reaction wheel capabilities),

- the nadir view must not approach the Sun,

- the time the platform spends away from the Earth heat load must be minimized,

- and the maneuver must be completed in no more than one orbit.

Reaction wheel capabilities are based on the memo entitled, "Assessment of a Modified Lunar Calibration Pitch Maneuver," TM-421-94-039 dated June 20, 1994 by P. Kudva [1]. The baseline CAM uses slightly under 50% of the momentum capacity of the reaction wheels.

A diagram of the baseline CAM is shown in figure 1. In the following description of the baseline CAM, times and rotation rates are approximate. In addition, the displacement of the Moon from the plane of the ecliptic (i.e. up to 5.15°) is ignored. The normal nadir angular velocity is assumed to be 0.06°/second. The finite distance of the Moon to the platform creates an apparent angular motion rate when the spacecraft is at the midnight ecliptic of 0.00114°/second. Approximately 20 minutes (or 73°) before the midnight ecliptic plane crossing, the pitch direction is reversed to -0.096°/second. This requires a pitch rate change of 0.156°/second and requires approximately 80 seconds using the four reaction wheels. This pitch rate is maintained during all observations. All the cameras of the Multi-angle Imaging Spectro-Radiometer (MISR) will cross the Moon, as well as at the nadir for pushbroom or whiskbroom scanning instruments. The apparent angular rate of the Moon is approximately a factor of 6 slower than the normal nadir rate. This provides a factor of 6 oversampling. Zero thermal background observations in which the Earth and Moon are cleared by at least 5° can be obtained any time between 1 to 12 minutes from the time the observations are centered on the Moon. For measurements of scattered light, data acquisition covering the region ±2° around the Moon will require approximately 42 seconds. It is desirable that during this data acquisition mode, platform motion should be as uniform as possible. When the Moon is in their scene, the high spatial science instrumentation can determine the inertial pointing much more accurately than the attitude engineering data. To aid in the reduction of instrument calibration data, uniformity of motion is more important than the absolute rate; and, therefore, it is desirable to avoid any torques on the reaction wheel system during these lunar observation periods. In addition, no instrument pointing should be attempted during this period. Approximately 20 minutes after the midnight ecliptic plane crossing, the platform approaches its original nadir orientation, the reaction wheel rates are returned to their initial velocity, and normal Earth nadir viewing is recovered.

This baseline CAM has the characteristics that nearly all of the maneuver occurs while the platform is in the Earth's shadow, and the platform nadir direction is at every point in the orbit farther from the Sun than in a normal orbit. Although the Earth's heat load is reduced throughout the maneuver, the period with no heat load extends from about 6.5 minutes before and after lunar observation.

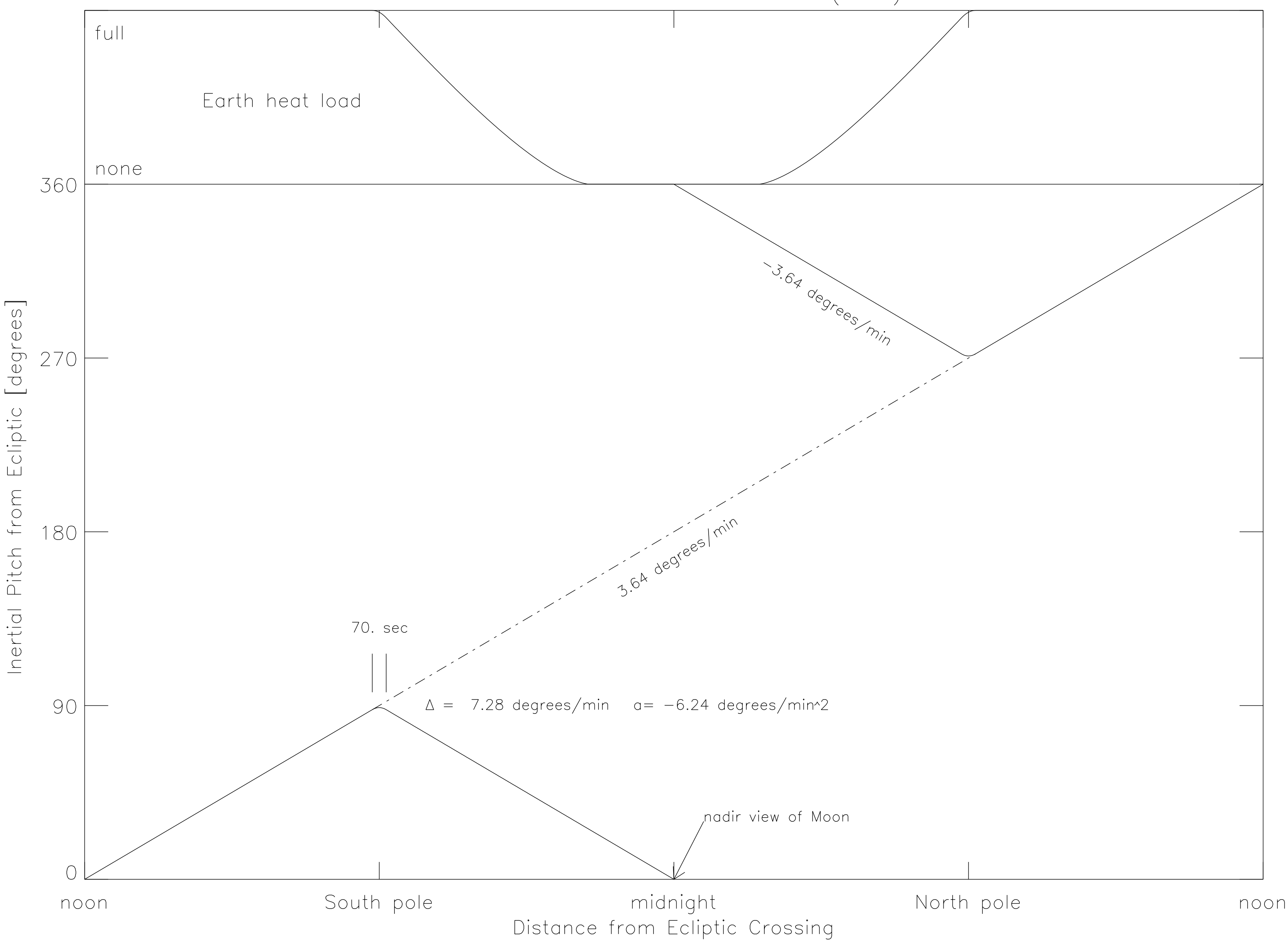
III. Description of Custom CAMs

There are a number of modifications to the baseline CAM and a number of non-baseline CAMs that for some instruments could potentially enhance the science value of the EOS AM-1 mission. Modified baseline CAMs and other non-baseline CAMS are referred to collectively as custom CAMS.

The only modified baseline or custom CAM studied by the AM-1 Project to date includes:

- performing a yaw of less than 20° before the baseline pitch maneuver and reversing the same yaw after the pitch maneuver (i.e. this would allow the instruments to view the Moon at smaller phase angles.),

- slowing the baseline reverse pitch rate briefly when crossing the Moon to allow larger oversampling factors, Calibration Attitude Manuever (CAM)



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- using more momentum capacity to shorten the off-nadir time and reduce the deviation from normal Earth heat load.

This custom CAM has been studied by the Code 421 EOS AM Project and is the subject of Lockheed Martin Astro Space memo numbered EOS-GNC-365 [2] and document numbered EOS-DN-SE&I-059 [3]. This maneuver is shown in figure 2. In this maneuver, the spacecraft is initially yawed 22° at 0.15°/second at the terminator. At the eclipse entry, the spacecraft is then commanded to pitch 110° at a rate of 0.175°/second. Following the pitch slew, the spacecraft is commanded to track the Moon. The Moon is capable of being scanned by the AM-1 instruments for up to 1 minute. Following the lunar viewing, the spacecraft is commanded to pitch 110° at 0.2°/second. The spacecraft is then commanded to track the nominal Earth reference frame.

Feasibility, risk identification, and implementation impacts are identified by Lockheed Martin Astro Space in document number EOS-DN-S&I-059 [3]. In brief summary, this analysis makes a number of assumptions up front. These include the following:

- The maneuver represents the consensus of the instrument community as formulated by the EOS AM-1 Project Scientist and Calibration Scientist. The maneuver has no impact on instruments not participating in the lunar calibration activity.

- Minor deviations from the designated maneuver are to be considered only in the event the subject maneuver is found to be non-feasible or overly constraining to the spacecraft subsystems.

- Lunar calibration maneuvers are expected to occur nominally at the beginning, middle, and end of the mission.

- The lunar maneuver is expected to allow for 10 to 60 seconds of lunar observation.

- Pointing accuracy requirements during the observation periods are constrained only by the need to keep the Moon in both the MODIS and ASTER fields of view. For this maneuver, the limiting case is the ASTER VNIR 5.5° half-cone field of view taken with the boresight centered along the spacecraft +z axis.

- The maneuver completion (return to nominal attitude) is expected to occur prior to exit from the eclipse.

- Due to concerns regarding instrument contamination, the maneuver is to be performed exclusively on reaction wheels. Use of thrusters for the nominal maneuver is not permitted,

- S-Band communications with TDRSS via the High Gain Antenna (HGA) are considered to be highly desired (nominally required).

- As the spacecraft design has already progressed through the Critical Design Review milestone, any significant design changes could result in substantial cost and schedule impacts. While not explicitly stated in the Task Assignment directive, it is understood that every effort should be made to make the maneuver compatible with existing hardware and that software and operational modifications would be considered first.[3]

Given the above constraints and assumptions, it was determined by Lockheed Martin Astro Space that the lunar calibration procedure (i.e. the Code 421 custom CAM described above) is feasible provided that four operational Reaction Wheel Assemblies (RWAs) are available. The maneuver cannot be performed on three wheels during eclipse. A failure due to any cause during the maneuver would prompt a transition to the Sun Pointing Safe Hold mode with thruster control. The instruments would be given advanced notification of this transition. The Lockheed Martin analysis shows the that the RWA equipment module temperatures are acceptable for the case of using 4 wheels. However, a preliminary thermal assessment indicates that the -z deck equipment modules may violate their module temperature requirements at end of life (EOL). Beginning of life (BOL) temperatures are within specification. Risk to the spacecraft during the maneuver can be mitigated by using the Three Axis Magnetometer (TAM) for attitude determination instead of the Earth Sensors. The TAM would be used in the Failure Detection, Isolation, and Recovery (FDIR) logic. Risk is also mitigated through implementation of full maneuver coverage via the HGA to TDRSS link. Finally, the maneuver represents changes to operation and software only and imposes no hardware changes on the spacecraft.

To date the aforementioned maneuver is the only one that has been extensively studied by the EOS AM-1 Platform Project. The study focuses on the spacecraft issues, not on the impacts to the instruments on performing this or any other CAM. The following section presents input from each of the AM-1 instruments on their operational constraints in performing CAMs in general. This is followed by a section in which each AM-1 instrument indicates the science benefits of performing the baseline CAM or specific custom CAMs.

IV. EOS AM-1 Instrument Engineering/Thermal Limitation to CAMs

The performance of CAMs on the EOS AM-1 platform will introduce the EOS AM-1 instruments to an environment which differs from that experienced during normal Earth viewing operation. These environments introduced by performing CAMs results in engineering and thermal issues which must be articulated by each instrument team and addressed by the platform. The engineering and thermal limitation information provided by the instrument teams is of paramount importance in determining the feasibility and risks of performing a particular CAM. The engineering/thermal limitations for each instrument are outlined below.

1. Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER):

The primary engineering concerns of the ASTER instrument concerning CAMs are in the areas of contamination and thermal changes to the optics. In order to not impact ASTER adversely, CAMs should be performed so that (1) the nadir direction does not go near the Sun, (2) no thruster activity is required, and (3) the time from the loss of planetary heat load until lunar viewing is approximately 20 minutes or less. The last constraint is to avoid the cooling of elements of the ASTER instrument to temperatures outside their operational temperature range.

2. Clouds and the Earth's Radiant Energy System (CERES):

At any time during a CAM, the CERES instrument must not directly view the Sun. In addition, the maximum science benefit derived from CERES is realized if CERES is able to determine its zero radiance offsets in a thermally stable environment. This environment is achieved if the portion of the CAM in which CERES scans deep space is conducted in the inertially-fixed geometry where the spacecraft nadir direction is constant with respect to the Earth-Sun direction. Whether the CAM is conducted in an inertially-fixed geometry or in the continuous pitch geometry, the CAM measurements will be useful to the CERES level 1 data processing effort. The CERES effort at NASA/Langley Research Center and the CERES Science Team have considerable experience in successfully applying CAM deep space radiometric measurements in the level 1 data processing algorithms.

3. Multi-angle Imaging Spectroradiometer (MISR):

No structural changes to the instrument are expected as a result of CAMs other than the structural changes that are thermally induced. That is, MISR expects the thermally perturbed boresight angles to return to their pre-maneuver values. However, the maneuvers are fairly complicated from a thermal perspective. In order to carry out an accurate thermal analysis on MISR for determining the thermal impact of a CAM, NASA/GSFC would need to run their EOS-AM-1 spacecraft thermal models to give MISR the environmental heat loads which would then be used in the JPL thermal models. This would be a time consuming task for both GSFC and JPL.

Nevertheless, the MISR team points out that it is possible to gain some insight on the thermal problem by taking a conservative approach and by thermally bounding the problem. This is done by carrying a transient analysis for a scenario where MISR begins in the normal science mode (i.e. with the nadir side facing Earth) and then transitions to a mode in which the nadir side points to deep space. The latter mode is equivalent to the sun-pointing safe mode (SPSM) which is one of the operational modes defined by NASA/GSFC. For quasi-steady state operations, this mode requires 80 to 90 Watts of heater power and most temperatures, including those of the electronics, optical bench, and cameras, drop to their minimum allowable non-operating levels (i.e. -25°C). Preliminary estimates of the rates of temperature drop are as follows:

- electronics: 0.15 to 0.2°C/minute
- cameras and optical bench: 0.1°C/minute.

Therefore, MISR has the following engineering/thermal constraints.

1. The minimum allowable operating temperature for the electronics is -10°C.

2. The worst-case minimum predicted electronics temperature is 3°C.

3. The minimum allowable operating temperature for the optics is 0°C.

4. The predicted camera and optical bench temperatures are in the range of 4 to 6°C.

Using the above information, the MISR team concludes that the CAM should not be performed if the time during which the nadir side of the spacecraft is viewing deep space exceeds about 40 minutes. In addition, any CAM must insure that the camera lenses avoid direct illumination by the Sun in order to avoid ultraviolet polymerization of any contaminants which would lead to a loss of transmittance.

4. Moderate Resolution Imaging Spectro-radiometer (MODIS):

MODIS' primary constraints on spacecraft maneuvers arise from the following:

- thermal changes,
- extended exposure to space debris from the ram direction (i.e. the +x direction).

The MODIS radiative cooler is designed to operate at approximately 80 to 82°K. Control limit heaters are applied to control the focal plane assemblies (FPAs) at a nominal temperature of 85±0.1°K. Temperatures of the cold FPAs rise slowly due to the thermal mass of the cold stage assembly. To limit the heat load input to the radiative cooler, the MODIS team prefers to conduct CAMs during the ~36 minutes between spacecraft sunset and sunrise and to prohibit exposure of the radiative cooler to the Earth’s surface. Thermal analysis of nighttime maneuvers has indicated that all pitches will, unless preceded by a 40 to 60° counter-clockwise roll about the +x axis, result in the radiative cooler exceeding its 85° control temperature and will require 1 to 2 days to recover.

The engineering and thermal effects of pitch, roll, and yaw platform maneuvers on MODIS are presented below.

Pitch Maneuvers:

The spacecraft continuously pitches about the +y axis one revolution per orbit (i.e. ~3.6°/minute or 0.06°/second) to maintain the Earth view centered on nadir. If the driven pitch is stopped (i.e. y axis inertial hold), the Earth field-of-view will cross above the local horizon (~64.2° from nadir) in approximately 17.8 minutes. This can be accomplished in approximately 11 minutes by driving the pitch axis in a counter-clockwise direction looking in the +y axis direction at a rate of 6°/minute (i.e. 0.1°/second). Pitch maneuvers in this direction shield the Earth aperture from the ram direction reducing the impacts of terrestrial space debris. Exposure to galactic meteoroids is increased up to a factor of two for deep space maneuvers since the shielding benefit from the Earth is lost. For occasional maneuvers, this is not considered to be a significant problem. For all simple pitch maneuvers started at spacecraft eclipse, the cooled detector temperature of MODIS is exceeded after a few minutes.

Roll Maneuvers:

Roll maneuvers are also limited to spacecraft night. Roll maneuvers in a counter-clockwise direction about the +x axis raise the radiative cooler away from the Earth and produce a small cooling effect due to the Earth scan cavity viewing space. Allowing approximately 1 minute for roll acceleration and 8 minutes for continuous roll at 6°/minute, MODIS can accomplish a 25° roll and return to nominal in less than 10 minutes. Clockwise roll maneuvers which lower the radiative cooler towards the Earth are more limited in duration due to the direct heat load from the Earth.

Yaw Maneuvers:

There are no MODIS constraints on yaw maneuvers (i.e. rotations about the z-axis) during spacecraft night. During the day modest (~20°) yaw maneuvers present no significant problem. Larger yaw maneuvers will require additional analysis.

5. Measurement of Pollutants in the Troposphere (MOPITT):

MOPITT would experience some thermal disturbance as a result of a CAM which might prejudice the data quality for some period of time. That period of time is expected to be on the order of one orbit or less. MOPITT assumes the maneuver would be completed in about 1/2 orbit and would not be repeated in successive orbits.

It is required that the optical ports of the MOPITT instrument do not receive direct sunlight at any time. This is for a number of thermal, contamination, and performance-related reasons. Although it is not thought that the instrument would be permanently and severely damaged by such an event, with a small amount of warning and assuming real-time commanding, the MOPITT mirrors could be moved into a safe position to further reduce the danger due to sun-viewing.

V. EOS AM1 Instrument Calibration and Characterization Uncertainties Without CAMS and Improvements With CAMs

Calibration Attitude Maneuvers or CAMS performed on the EOS AM-1 and successive platforms provide instruments with an Earth-port view not only of the Moon but also deep space. Lunar views provide the instruments with a common, in-flight, radiometrically stable and well characterized target for the determination of instrument responsivities. Lunar views also provide the instruments with a measure of their stray light sensitivity. The appearance of the Moon as a bright target on a black background provides instruments with a target for the characterization of Modulation Transfer Functions (MTFs).

There are many qualitative and quantitative benefits of performing CAMS on the inflight calibration and characterization of instruments and ultimately on the accuracy and precision of the instruments' level 1 radiance product. These benefits are outlined below by first presenting the approach to instrumental calibration and characterization assuming CAMS are not performed followed by the improvements obtained by performing both the baseline and any desired custom CAMS. This information is presented for each EOS AM-1 instrument.

1. Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER):

A. Without CAMS:

In the absence of performing CAMS, ASTER will depend strongly on the on-board calibrators (OBCs) for the in-flight determination of absolute sensor responsivity. The VNIR and

SWIR employ redundant OBCs which are designed to meet the 4% (1 sigma) calibration accuracy specification. Unfortunately, these OBCs are not full aperture calibrators. In addition to the OBCs, ASTER will use a variety of nadir-viewing vicarious calibration methods. The most accurate is expected to be a radiance calibration using simultaneous airborne underflight measurements from calibrated radiometers. Apart from scene uniformity considerations, this method is anticipated to have an uncertainty near 2%. Previous experience with similar calibrations of the SPOT instrument has produced uncertainties of 3%.

ASTER will determine its spatial response function on-orbit by viewing sharply defined high contrast borders and targets on the earth's surface. Because the ASTER IFOV is a small fraction on the atmospheric scale height, it will be difficult to separate instrumental MTF from atmospheric MTF (i.e. the "adjacency effect").

The inflight operation and calibration of the ASTER Thermal Infrared (TIR) subsystem departs substantially from previous TIR instruments. The ASTER TIR subsystem has no access under normal circumstances to a view of space. As a result the DC offset of the subsystem is established by viewing an internal reference surface (i.e. on-board blackbody) at a constant temperature. In this short-term calibration mode, the reference surface is viewed at the beginning and end of each observation sequence. Approximately once a month, the reference surface is also used in a long-term calibration mode in which the temperature of the surface is varied. Assuming an effective radiation temperature of the surface, measurements of the reference surface in this operating mode allow the conversion of data numbers to at-aperture radiances and enables the determination of gain variations and DC offsets. The time to change the reference surface temperature is relatively slow; the thermal effects on the remainder of the sensor have been modeled to be small, but the method is unproven.

B. With the Baseline CAM:

Assuming that the baseline CAM is performed, ASTER will use views of the Moon against deep space as a monitor of ASTER responsivity and long-term radiometric stability in the VNIR and SWIR bands. Because a large number of ASTER pixels will fall on the Moon, the effective signal to noise ratio will be in excess of 1000 and the measure of radiometric stability will be limited by the differential error in the lunar radiometric model. This error is expected to be less than 0.2%. Thus, the lunar baseline CAM is expected to provide an order-of-magnitude improvement in the long-term stability of the ASTER radiometric product. This improvement is particularly important for observing changes in the terrestrial environment, such as the creep of desertification or the localized loss of soil. Because the ASTER linear spatial resolution is more than an order of magnitude higher than other EOS AM-1 instruments, the improved ASTER radiometric product will be of great utility for detecting these surface changes.

The knowledge of the in-flight IFOV performance of ASTER derived from lunar observations will translate to improved geometric resolution in the level 1 product. The bright limb of the Moon will provide an ideal "knife edge" for determining the near off-axis response and scattered light sensitivity of ASTER. At full Moon, these can be determined for all radial directions.

Assuming that the baseline CAM is performed, ASTER will use views of deep space to directly determine the zero point DC offset of the TIR bands without any assumptions about radiation temperature, system spectral response or gain. The DC offset determined from a deep space view will be compared with that deduced from the reference surface determinations and adjustments will be made to account for differences. This direct determination of the offset provides an independent check of the in-flight calibration procedure and is therefore an extremely valuable additional step in ensuring that ASTER produces accurate results of known uncertainty.

C. With Custom CAMS:

The baseline lunar CAM provides ASTER with all the capabilities outlined above. In addition, if a cross-track lunar scan is executed as desired by MODIS for determination of scan mirror uniformity, then the ASTER TIR mirror scan uniformity could also be determined.

2. Clouds and the Earth's Radiant Energy System (CERES):

A. Without CAMS:

At the 1 sigma level, laboratory calibrations of the CERES proto-flight model (PFM) sensors indicate that the sensor zero radiance offsets can vary as much as 1 W/m^2 sr (i.e. 5 digital counts) as a function of scan geometry. This translates to an absolute radiometric uncertainty of 2% for a typical shortwave Earth measurement of 60 W/m^2 sr and 1% for a typical longwave measurement of 80W/m^2 sr. If a CAM which enables CERES to scan deep space is not conducted, the CERES absolute goals of 0.5 and 0.8W/m^2 sr will not be realized at the instrument level for each CERES footprint measurement. Measurements of the nightside of the Earth by CERES will allow the determination of the radiometric offsets of the shortwave sensors at a reduced accuracy. For the total wavelength and the 8 to 12mm window sensors, scanning measurements of the inside of the instrument contamination covers might yield some information on the longwave offsets. However, in order to meet the CERES absolute radiometric goals, a CAM enabling CERES to scan deep space limb-to-limb is needed.

B. With the Baseline CAM:

The CERES instrument radiometric DC offsets will be determined in-flight every 6.6 seconds by measuring the radiance of cold space at viewing geometries between the spacecraft and the Earth's limb. These offsets will be applied to Earth-viewing measurement geometries. While the Moon cannot be used in the radiometric calibration of the CERES sensors, the deep space view afforded the CERES sensors by performing the baseline CAM will eliminate measurement geometry related uncertainties in the DC offset measurements. This uncertainty will decrease to the 0.1% level.

C. With Custom CAMS:

CERES does not require custom CAMS per se. CERES supports any orbital geometry which (1) allows deep space to be observed for approximately 20 minutes and which (2) allows deep space to be observed at geometries in which the Earth radiance measurements are conducted (i.e. in the hemisphere centered around the nominal spacecraft nadir direction). However, as stated in Section IV Part 2, the maximum science benefit to CERES from a CAM is realized if CERES is able to determine its zero radiance offsets in a thermally stable environment. This environment is achieved if the portion of the CAM in which CERES scans deep space is conducted in the inertially-fixed geometry where the spacecraft nadir direction is constant with respect to the Earth-Sun direction. CERES points out that whether the CAM is conducted in an inertially-fixed geometry or in the continuous pitch geometry, the CERES measurements obtained during the maneuver will be extremely useful to the CERES level 1 data processing effort.

3. Multi-angle Imaging Spectroradiometer (MISR):

A. Without CAMS:

The MISR instrument will incorporate an On-Board Calibrator (OBC) consisting of deployable Spectralon™ panels to reflect diffuse sunlight into the cameras along with several sets of photodiodes. Photodiodes which will be used include high quantum efficiency (HQE) photodiodes in a light-trapped configuration and radiation-resistant PIN photodiodes. MISR will use a detector-based calibration; and therefore will rely on these photodiodes to provide the primary calibration for the instrument. The photodiodes will detect changes in (1) the transmittance of the optical elements of the cameras, (2) the quantum efficiency of the camera CCD detectors, and (3) the reflectance of the Spectralon™ diffusers. In-flight calibrations using the OBC will be performed monthly.

B. With the Baseline CAM:

The MISR instrument is designed to meet its performance specifications without reliance on any CAMs. Because the Moon does not completely fill the MISR swath width and the Moon will be viewed by MISR in instrument configurations different from those used in Earth viewing, lunar views will not provide any enhancement to the in-flight absolute radiometric calibration of MISR. However, lunar views afforded by the baseline CAM will provide an independent stability verification for the MISR instrument. The lunar view will enhance confidence in the MISR calibration strategy and will indicate the validity of the MISR radiometric uncertainty values. The continual pitch motion provided by the baseline CAM will provide pushbroom imaging of the entire lunar disk. Repeated lunar views will be co-registered for MISR stability verification using the lunar limb and lunar features. In addition, observations of the sharp edge of the lunar limb will provide a means of verifying the instrument point spread function and MTF response. Accumulated charged particle radiation damage to the MISR camera CCDs will degrade their charge transfer efficiency over the lifetime of the mission for signals below 10% equivalent reflectance. Since most dark scenes observed by MISR (e.g. the open ocean) are spatially uniform, this degradation will not adversely impact the experimental science objectives. However, periodic observations of the Moon will enable a characterization of this effect relative to an early mission baseline and will provide greater confidence in our understanding of the stability of the instrument with time.

C. With Custom CAMS:

The baseline CAM is the most useful maneuver to MISR for two principal reasons. First, the continual fast pitch motion provides a view of the Moon in all nine of the MISR cameras as well as the calibration diodes. A pitch hold maneuver would provide a lunar view in only the nadir camera. Second, the MISR camera line arrays resolve the lunar disk; and pitch hold provides only a single line of imagery in each of the nadir camera bands. In addition, the location of this single line of imagery is uncertain by 2.5 arcmin out of the 31 arcmin lunar diameter. Thus, it would be difficult to guarantee that repeated looks of the Moon produced views of the same spot on the lunar disk. On the other hand, the continual pitch motion as provided by the baseline CAM will enable MISR to image the entire lunar disk and repeated looks at the Moon can be co-registered using the lunar limb and features on the lunar disk.

The modification to the baseline maneuver in which the platform is yawed to provide lunar observations near full Moon provides no advantages to MISR's use of the Moon as a stability check. However, the baseline maneuvers with and without the yaw are equally suitable to MISR.

4. Moderate Resolution Imaging Spectro-radiometer (MODIS):

A. Without CAMS:

The MODIS scan mirror is a two-sided beryllium structure overcoated with nickel, silver, and SiO_x. Modeling and measurements by SBRC have shown that the reflectivity varies across the ±55° scan angle by 1 to 2% in the visible and near infrared and by 10 to 15% in the thermal infrared. Ideally, the reflectance of the mirror measured prelaunch should remain constant through launch and postlaunch. If the functional form of the scan mirror reflectance versus angle of incidence (AOI) is the same on-orbit as it was during prelaunch testing, changes in reflectance could be accounted for using information from the on-board calibration systems. However, there are distinct possibilities that the spectral reflectance curve of the overcoated silver will change shape on-orbit as a result of physical damage or contamination.

The uncertainty in the MODIS scan mirror relative reflectance will contribute to the uncertainty of the MODIS radiometric products. This is especially true for the MODIS thermal bands (SW/MWIR and LWIR bands 20-25 and 27-36), due to thermal emission from the scan mirror, which varies with the AOI. The emittance of the MODIS scan mirror is such that there is an appreciable scan angle dependent output from the system with zero radiance at the entrance aperture. The scan angle dependent emission from the scan mirror can be measured by maneuvering the spacecraft to allow a 110° view of deep space through the Earth view port. Preliminary estimates suggest that a 10° margin between the limits of the 110° field-of-regard and the Earth limb should be sufficient. In addition, it will be necessary to maintain the full field-of-regard view of deep space for about 10 minutes to ensure the acquisition of enough data for signal averaging to achieve the necessary sensitivity. There are no precise pointing requirements for this maneuver operation. Analyses by G. Godden, E. Knight, and B. Guenther of the MODIS Characterization Support Team (MCST) reported at the 1995 Utah State Infrared Calibration Symposium suggest that expected amounts of spacecraft outgassing will cause reflectance changes exceeding allowed budgets. This dictates a requirement for periodic measurements of the scan mirror relative reflectance with angle throughout the mission to maintain calibration uncertainties within the allowed budgets. It is conservatively estimated by MCST that without the spacecraft maneuvers, the relative reflectance of the scan mirror at all angles will not be known to better than about 1.0%. Based on analyses of the MODIS Engineering Model thermal vacuum measurements while viewing a cold target through the space view port (AOI=11.5°), the scan mirror relative reflectance can be measured to an uncertainty of 0.2% using 10 minutes of data. Thus, with the spacecraft maneuver, it should be possible to measure the relative reflectance of the scan mirror at all angles to 0.2%.

Figure 3 shows the effect of scan mirror relative reflectance uncertainty on the MODIS radiometric product. From this chart it is apparent that a view-of-space maneuver will provide essential data to bring 8 thermal bands to within or near compliance when comparing the predicted measurement uncertainty capabilities (~0.2%) with the expected prelaunch measurement uncertainty capabilities (~1.0%). Note that these results portray expected uncertainties relative to 100% of the specified uncertainty. Since there are other sources contributing to the measurement uncertainties, the comparison should be to something less than 100% of the allowed budgets.

Without CAMS MODIS will radiometrically calibrate its reflected solar bands at a single scan angle using the on-board calibrators, and any functional change in the scan mirror reflectance versus AOI for this wavelength region will be undetected. CAMS will enable MODIS to scan the Moon and determine the AOI dependence of scan mirror reflectance in the solar reflected wavelength region.

Based on previous determinations of the optical throughput loss rate of satellite instruments such as AVHRR[4-7], CZCS[8], and SAGE II, it is reasonable to predict an optical throughput loss rate for MODIS and other EOS payload instruments of 2 to 6% per year. If it is assumed that the entire transmission loss is undetected, then the inaccuracy of the MODIS system in a worst case scenario will exceed the specified limits a few months after launch. In reality the on-board calibrators will determine the offset of the change in reflectance at a single angle and the AOI dependence will remain unknown. The fractional part of the transmission loss due to contamination and high velocity cosmic dust is speculative at this time. However, if a fraction of the predicted 2 to 6% yearly loss in optical transmission is AOI dependent, the MODIS thermal bands will exceed their inaccuracy specification in a fraction of a year and the VIS/NIR bands will exceed theirs in 1 to 2 years.

B. With the Baseline CAM:

As mentioned previously, the baseline CAM will result in loss of all MODIS thermal bands for 1 to 2 days. However, post-launch spacecraft maneuvers (ie. the baseline CAM and custom CAMS presented below) will enable three types of on-orbit MODIS calibrations/characterizations to be performed. These include the following: (1) a substantial increase in the number of VIS/NIR lunar observation opportunities, (2) an ability to monitor changes in system throughput across the +/-55° swath of MODIS, and (3) an opportunity to radiometrically compare the MODIS on AM-1 with the MODIS on PM-1.

C. With Custom CAMS:

Custom CAMs are essential in maintaining MODIS postlaunch calibration and characterization. Custom maneuvers which enable MODIS to either view and/or scan across the Moon or deep space are outlined below.

1. Small Rolls of the Spacecraft:

The average number of opportunities for the MODIS instrument to view the Moon through its space view port is 5 per year. In these views, the Moon produces illumination at an angle of incidence on the MODIS scan mirror of 11.4° at 67.5° after full Moon. The number of lunar viewing opportunities can be increased to 12 to 13 times per year by rolling the AM-1 platform 25° or less. Performing these small rolls of the platform provides some additional opportunities for MODIS to view the Moon through its Earth view port at scan mirror angles of incidence (AOIs) of 10° to 20°. In an effort to monitor solar diffuser degradation, MODIS desires that this roll maneuver be performed at an initial frequency of at least once per month with a final frequency which is to be determined.

2. Five Step Maneuver of the Spacecraft:

MODIS requires a five step lunar viewing maneuver which meets the following measurement goals and is within the following constraints:

- viewing the Moon at scan angles incident on the MODIS mirror from at least 0° to 55°,
- prohibiting exposure of the MODIS radiative cooler to sunshine at any time during the maneuver,
- minimizing the radiative cooler exposure to earthshine,
- avoiding rates of platform rotation in excess of 7.0° per minute.

A sample five step maneuver sequence that meets all the requirements/constraints is shown in figure 4. As indicated in the top left of figure 4, an observational frame of early fall and a lunar phase of 67.5° are assumed as dictated by the above constraints. The following five blocks of information going down the left side of the page list the five step maneuver sequence. Briefly, the five step maneuver is as follows:

1. a -50.00° roll of the spacecraft starting -40.12° before the sub-satellite terminator and ending 11 minutes later at the sub-satellite terminator;
2. a 3.81° pitch and a -15.00° roll starting at the sub-satellite terminator and ending 3 minutes later 10.94° after the sub-satellite terminator;
3. a -66.84° pure roll of the spacecraft starting 10.94° after the sub-satellite terminator, lasting 12 minutes, and ending 54.71° after the sub-satellite terminator (this passes the Moon across _ of the MODIS swath as shown in the middle graph);
4. a roll/pitch maneuver starting 54.71° after the sub-satellite terminator and ending 105.77° after the sub-satellite terminator, lasting 14 minutes and positioning the platform at a roll/ pitch attitude of -45.00°/15.00° from the nominal platform earth-viewing attitude;
5. a roll/pitch maneuver starting 105.77° after the sub-satellite terminator and ending 131.30° after the sub-satellite terminator, lasting 7 minutes and returning the platform to its nominal earth-viewing attitude.

Note that in figure 4, the attitude information listed in step 1 and step 4 relates to the platform attitude at the end of these steps relative to the nominal platform earth-viewing attitude. The attitude information listed in step 2 and step 3 is obtained by executing the prescribed rotations of steps 1 and 2 and steps 1, 2 and 3, respectively. Figure 4 also presents the minimum angle, Y_m, between the sun and the MODIS radiative cooler surface and the maximum projected solid angle subtended by earthshine incident on the cooler surface. Finally, figure 4 shows the platform body rotational rates for each step in the five step sequence. Note that 4 of the 5 steps are 3 axis maneuvers with step 3 being a simple 1 axis maneuver.

In an effort to accommodate the lunar viewing needs of the MISR instrument, the MODIS instrument devised a lunar calibration maneuver which enables MISR to view the Moon in all its cameras and which can be performed in the orbit immediately preceding or following the MODIS maneuver. The requirements and constraints in designing the MISR maneuver are listed as follows:

- prohibiting exposure of the MODIS radiative coolers to sunshine at any time during the maneuver,
- minimizing the radiative cooler exposure to earthshine,
- avoiding rates of platform rotation in excess of 7.0° per minute,
- viewing the Moon at pitch angles ranging from at least -60.00° to 60.00°, so that all MISR cameras will scan across the Moon.

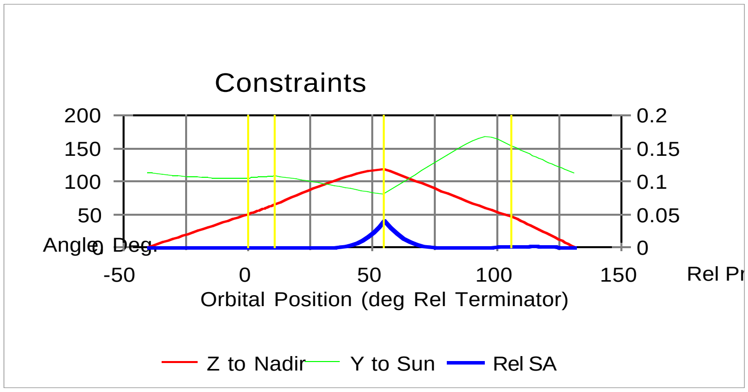
Figure 5 describes a five step maneuver sequence that meets all the aforementioned requirements. This maneuver follows the pattern of the MODIS maneuver described in figure 4 with the exception that in the MISR maneuver step 3 is a uniform rotation about the pitch axis through the listed pitch angle. Again, the lunar phase of 67.5° and the observation frame of early fall are chosen so that lunar calibration viewing by MISR and MODIS can be accomplished in two consecutive orbital periods.

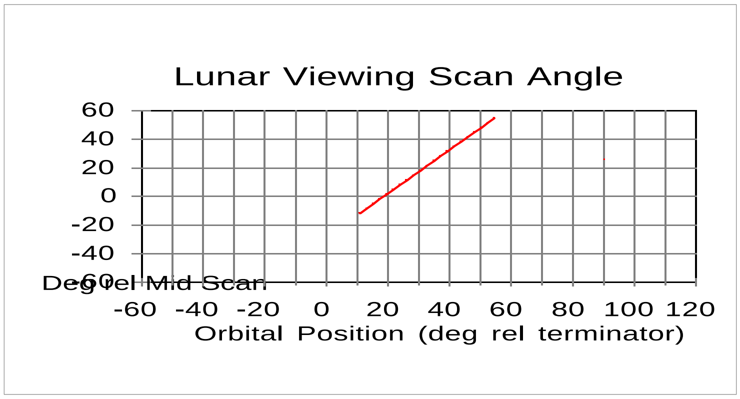
The desired frequency of the MODIS maneuver is once per year with several additional maneuvers during the Activation and Evaluation (A&E) phase.

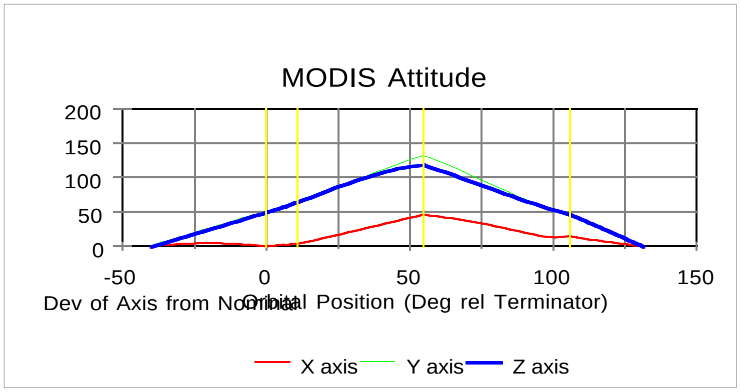
3. EOS AM-1/PM-1 Joint Maneuvers to Enable Cross-calibration of AM-1 and PM-1 MODIS:

Date	34963		
Lunar Pha	67.5	0 Deg	
Roll1	-50	Deg	
Pitch1	0	Deg	
Orb Strt	-40.118	Deg	3.6471
Step1 Dui	11	Min	
Orb End S	0.0006	Deg	
Pitch2	3.809	Deg	
Roll2	-15	Deg	
Scan2	-11.839	Deg	
Step2 Dui	3	Min	
Orb End S	10.942	Deg	
Roll3	-66.839	Deg	
Step3 Dui	12	Min	
Orb End S	54.708	Deg	
Step4 Dui	14	Min	
Roll4	-45	Deg	
Pitch4	15	Deg	
Orb End S	105.77	Deg	
Step5 Dui	7	Min	
Orb End S	131.3	Deg	
Min Ym to	98.567	Deg	
Max Rel P	0.0407		
Space Loc	22.44	Min	

Body Rot.	Roll	Pitch	Yaw
Step 1	-4.3535	-3.409	-1.5896
Step 2	-4.8969	-0.7054	-2.9156
Step 3	-5.5699	0	0
Step 4	5.6366	0.2345	-6.847
Step 5	6.5311	-5.4844	-0.6018





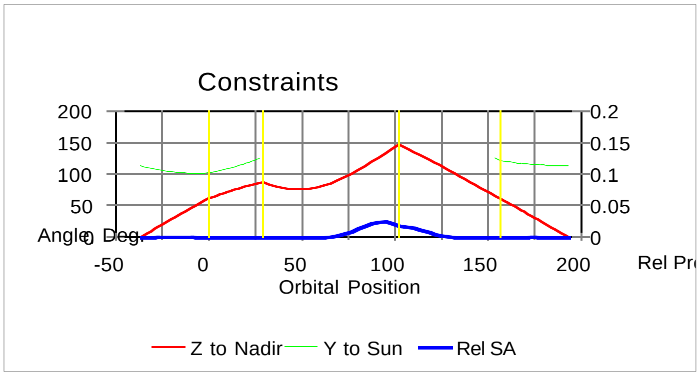


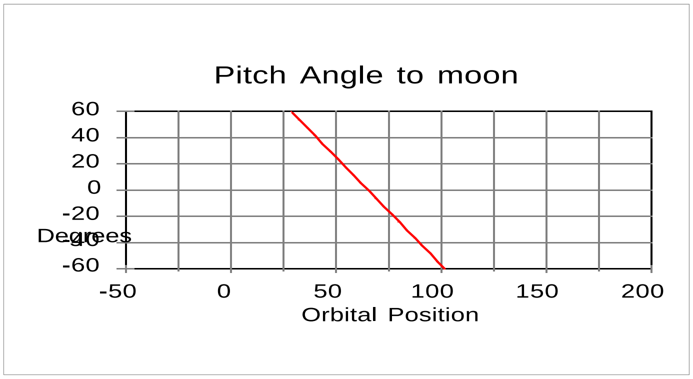
* Lunar Phase is relative to full moon being 0.0 degrees
** During the period the sun is not occulted by the earth
*** When the Z to Nadir angle is greater than 64.2 degrees

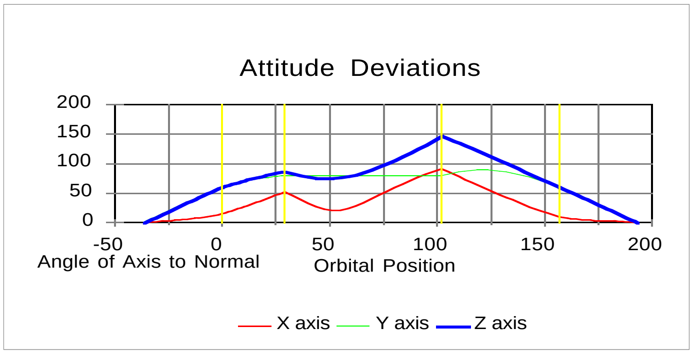
A Sample MODIS Lunar Calibration Maneuver

Date	34963		
Lunar Pha	67.5	0	Deg
Roll1	-60	Deg	
Pitch1	-15	Deg	
Orb Strt	-36.471	Deg	3.6471
Step1 Dui	10	Min	
Orb End S	0	Deg	
Roll2	-19.848	Deg	
Pitch2	-38	Deg	
Pitch Angl	59.479	Deg	
Step2 Dui	8	Min	
Orb End S	29.177	Deg	
Pitch3	120	Deg	
Step3 Dui	20	Min	
Orb End S	102.12	Deg	
Step4 Dui	15	Min	
Roll4	-60	Deg	
Pitch4	10	Deg	
Orb End S	156.83	Deg	
Step5 Dui	10	Min	
Orb End S	193.3	Deg	
Min Ym to	100.34	Deg	
Max Rel Pi	0.0246		
Min Ym -H	-4E-14	Deg	

Body Rot.	Roll	Pitch	Yaw
Step 1	-6.082	-4.6557	-1.1531
Step 2	-4.2774	-5.8574	-2.1672
Step 3	0	6	0
Step 4	6.0323	-5.1507	-6.0331
Step 5	5.991	-4.2055	-1.4091







* Lunar Phase is relative to full moon being 0.0 degrees

A Sample MISR Lunar Calibration Maneuver

Custom CAMS also provide MODIS the opportunity to radiometrically compare the MODIS on AM-1 with the PM-1 MODIS. Normalization of the AM-1 and PM-1 MODIS data requires measurements from the same target by both sensors. Earth scenes are difficult to use due to the temporal variability of the atmosphere. The Moon is a good target to use for this purpose, but it must be viewed at the same phase by both sensors. The latter requires a maneuver by at least one of the two spacecraft. A 135° roll will enable AM-1 to view the Moon at the same phase that PM-1 MODIS will collect lunar data. This will eliminate any offsets between the AM-1 and PM-1 data. The details of these joint maneuvers are TBD. The desired frequency of these maneuvers is once during the time in which the AM-1 and PM-1 platforms are on-orbit.

5. Measurement of Pollutants in the Troposphere (MOPITT):

A. Without CAMS:

MOPITT is an infrared viewing instrument operating at 2.4 and 4.7 microns with a square IFOV of 1.75°. On-orbit MOPITT will use on-board blackbodies and a space zero for radiometric calibration.

B. With the Baseline CAM:

The MOPITT instrument is designed to operate successfully without CAMS. The Moon is unsuitable as a calibration source for MOPITT. The Moon at a size of approximately 0.5° does not definitely and reproducibly fill the MOPITT field of view. In addition, the Moon is not sufficiently small enough to be considered a point source for MOPITT. The radiance levels provided by the Moon at the MOPITT wavelengths is small since the "fill factor" of the field (i.e. on the order of 6.5%) is small and the source is not much brighter than strong terrestrial targets. For these reasons, any deductions from a lunar calibration are likely to be arguable and may defeat the intent of a stable calibration. Another issue is that of the utility of a deep-space view afforded by the CAM particularly with respect to the issue of determining "scan-dependent strays." In this area the CAM may have more utility but the results must be tempered by the following considerations. First, the out-of-field environment of the instrument is different (i.e. the strays external to the instrument are different). Second, the thermal environment is changing due to the change in external (nadir) energy coupling through the ports. The MOPITT team is unable at this time to quantify whether there would be any useful information to be gained through this avenue.

C. With Custom CAMS:

The MOPITT response with respect to the baseline CAM also applies to custom CAMS.

VI. Instrument Cross-calibration Using the Moon

The cross-calibration of sensors used for global change studies is of great importance. When three or more sensors on the same platform or on successive platforms are cross-calibrated, the results can be used to identify calibration differences between sensors and to diagnose systematic errors such that a mutually consistent set of data can be obtained for accurate quantitative analysis. Cross-calibration is facilitated if the sensors have similar spectral responses and if they acquire the same scene at the same time and viewing angle. An obvious example of the advantages of using the Moon is provided by the ASTER, MISR, and MODIS sensors on the EOS AM-1 platform. With a spacecraft maneuver all three sensors can acquire the Moon along their nadir line-of-sight. Less obvious, but of particular importance for the maintenance of consistency in decadal-long, global land data sets, is the comparison of sensors on successive platforms. An example of this is the calibration of MODIS sensors on the AM-1 and PM-1 platforms. (The implications on the CAM needed to perform this were briefly discussed in the MODIS entry to Section II.) Cross-calibration of sensors on successive platforms can be made by arranging for the two sensors to view the Moon in the same phase during the last operational orbits of the first sensor and the first operational orbits of the second sensor. The importance of CAMs in the cross calibration of instruments on successive platforms increases in light of the current interest in reducing the mass and volume of EOS instruments for later missions. CAMs may become more frequent components of later mission calibration strategies, and the implementation of a CAM on AM1 would provide linkage between these data sets over the projected decadal time scales of the EOS missions.

The Moon provides a target that can serve two purposes. The Moon can be used to track the change with time of the response of two or more sensors. The Moon, when well spectrally calibrated, can provide an accurate absolute determination of the differences in the calibration of the sensors. Under optimum conditions the accuracy of the cross-calibration may be better than 1%.

A simple example of the use of lunar views in the cross- calibration of sensors on the same platform has been provided by Kurt Thome of the University of Arizona Optical Sciences Center for the case of MODIS and ASTER on AM-1. This example is shown in Table 1. In this analysis a spectrally flat scene and the presence of an intervening atmosphere is assumed. The presence of the intervening atmosphere, of course, does not hold if the Moon is the scene. The interaction between the differences in the instrument center wavelengths and bandpasses of their spectral responses with the solar spectral distribution and the spectral variations of atmospheric scattering and absorption give rise to the following differences. Because there are significant atmospheric absorptions for all but ASTER band 1, the differences should be noticeably less when the Moon is used for the comparison. Note that even though the bands do not match well, the agreement in the VNIR is good. With corrections for the different solar distribution samples due to bandpass differences, the percent differences could be significantly reduced.

Table 1. Cross-calibration Analysis of ASTER and MODIS on EOS AM-1

ASTER Band No.	ASTER Wavelength (nm)	MODIS Band No.	MODIS Wavelength (nm)	In-band Spectral Radiance % Difference
1	520-600	4	545-565	1.5
2	630-690	14	673-683	0.9
3	760-860	2	841-876	1.9
4	1600-1700	6	1628-1552	2.9

The above example assumed that the surface was spectrally flat. In the case of the Moon this is not so, although casual observation indicates that the Moon is not a colorful object. The average lunar reflectance increases from approximately 0.05 at 400 nm nearly linearly to approximately 0.33 at 2500 nm. The primary spectral features are smooth absorptions near 950 nm and 1900 nm. Both features are approximately 500nm wide and 10% in depth [9,10].

However, to achieve the highest accuracy, the integrated spectral distribution of the Moon has to be known. The integrated value is necessary because all pixels over and around the Moon that show any response will be summed for each sensor. This avoids pixel registration problems over the Moon's non-uniform surface. The lunar radiance model (Section VI) will have primary observations in 23 bands in the VNIR. Higher spectral resolution observations of the major lunar surface types [9, 10] can be used to interpolate the photometric parameters of the radiance model in wavelength between these bands on and individual 15 meter pixel basis. Additional measurements from the ground will be necessary to extend this range into the SWIR.

Although the relative and absolute accuracy of cross-calibration using the Moon has yet to be proven, there is good reason to believe that, with an accurately known integrated spectral distribution for the near-full Moon, the accuracy of the cross-calibration will be about 1% and possibly limited only by the noise equivalent radiance differences of the sensors.

VII. The Lunar Radiance Model

To instruments on the AM-1 platform, the Moon appears to have a diameter of 6.4km. Although the radiance of the Moon varies across its face and is a strong function of phase angle, the intrinsic spectrophotometric properties of the Moon are stable to ~$1x10^{-9}$/year. A ground-based observing program is underway to measure lunar radiance in a number of bandpasses with spatial resolution equivalent to 15 meters per pixel. The objective of this observational program is to improve knowledge of lunar radiometry to the order of 2%. This program will develop a model of lunar photometry, including the effects of lunar libration, that can generate radiance models of the Moon corresponding to specific spacecraft observations. This program is described by Kieffer and Wildey [11].

Current uncertainty of lunar irradiance is about 15%. Table 2 indicates the lunar irradiance expected for several phase angles relevant to the AM-1 platform. These values are based on the work of Lane and Irvine [12]. Due to the strong backscatter of the lunar surface (i.e. the opposition effect), the dynamic range available from the Moon increases substantially at small phase angles. However, phase angles less than 2° should not be used in order to avoid eclipse phenomena. In addition, the inclination of the Moon's orbit limits the number of viewing opportunities at angles less than 5°.

The lunar radiometric measurement program will develop a detailed photometric model of the Moon in each band. These bands are listed in Table 3. This model can produce a radiance image corresponding to the precise geometry of a spacecraft observation with a resolution equivalent to 15 meters per pixel. This can then be compared to the AM-1 instrument level 1 product. Wavelength interpolation, where required, will be done at the pixel level using spectra of appropriate lunar material. Analysis methods using the lunar radiance image data and EOS instrument data include the following:

Table 2. Effective Reflectance on the Lunar Disk

		Phase Angle		
Wavelength (microns)	Geometric Albedo	~4°	22.5°	67.5°
0.3590	0.072	0.0720	0.040	0.013
0.3615	0.077	0.0770	0.041	0.013
0.3926	0.085	0.0850	0.048	0.016
0.4155	0.088	0.0880	0.049	0.016
0.4400	0.094	0.0940	0.053	0.017
0.4573	0.098	0.0980	0.055	0.018
0.5012	0.106	0.1060	0.600	0.020
0.5480	0.113	0.1130	0.065	0.022
0.6264	0.162	0.1620	0.093	0.031
0.7297	0.179	0.1790	0.105	0.036
0.8595	0.179	0.1790	0.107	0.037
1.0635	0.202	0.2020	0.123	0.045
1.2400	0.226	0.2258	0.137	0.050
1.3750	0.244	0.2436	0.148	0.054
1.6400	0.265	0.2654	0.148	0.054
2.1300	0.303	0.3030	0.184	0.067

(1) Lunar irradiance method: The radiance model is summed over all pixels and compared with the sum of the instrument level 1 product pixels. This requires accurate knowledge of the instrument scan rate past the Moon. If not known by independent means, this scan rate can be derived from the image itself. This method yields a high signal-to-noise ratio (SNR) because of the involvement of many instrument measurements. A first-order approximation of the SNR improvement factor is presented in Table 4.

(2) Cross-plot of each instrument pixel method: The position and extent of each instrument pixel on the lunar radiance model is calculated, and the lunar radiance is summed for that area. The instrument level 1 product is then compared on a pixel-by-pixel basis (i.e. a cross-plot). There will be scatter due to the instrument SNR for single pixels plus any incorrect estimation of the point-spread function of the detectors. Any deviation of the slope from unity indicates a calibration discrepancy, and curvature indicates non-linearity.

(3) Off-axis response and scattered light method: From space the radiance background

surrounding the Moon is nearly zero; the cosmic background of 4°K overlain with stars and galaxies. The brightest star ever near the Moon, Aldeberan, is 4×10^{-6} the brightness of the Moon. For a 1 km pixel this star is about 10^{-4} as bright as the lunar surface at full Moon. For this reason, it is desirable to extend the lunar observations beyond the limb of the Moon. Also, using the lunar radiance model, scans across the bright lunar limb can be inverted to yield the line-spread function or MTF. For a high resolution instrument, this is similar to a classic knife-edge test.
Determination of instrument stability depends only on errors in the derivative of the lunar model across the range of phase and libration angles used. The phase angle of the Moon changes at a rate of 1/2 degree per hour or less. Thus, with a 100 minute satellite orbit, the phase angle can be repeated to within 0.5 degrees.

An accurate model of lunar radiance in the shortwave infrared is not available. Due to the low thermal inertia of the lunar soil, near midday the lunar surface is near thermal equilibrium; and peak brightness temperatures reach 400°K [13]. Sarri and Shorthill based their absolute calibration on a calculated temperature for the sub-solar point; the uncertainty is not well constrained. The reflectance model being developed will allow calculation of the bolometric albedo distribution across the Moon to better accuracy than previously available. In addition, a nominal lunar thermal model can be generated which will contain the basic features of lunar thermal emission. Variation of lunar spectral emissivity across the Moon is a few percent [14, 15]. However, accounting for the variation of thermal inertia across the Moon, primarily related to the fractional abundance of exposed blocky material, would require a substantially larger modeling effort.

Thermal emission can contribute up to 10% of the observed radiance at 2.5 microns; this radiance will be incorporated into the lunar radiance model.

Table 3. Lunar Spectral Bandpasses

Visible Band Center Wavelengths (nm)	FWHM (nm)	Stellar Band
348	36	u
352	35	u
405	18	v
413	14.5	c
415	20	v
443	11.2	c
467	26	b
476	22	b
488	8	c
544	22	y,V
551	9.5	c
554	20	y,V
667	9.5	c
694	19	R
705	19	R
747	10	c
765	18	
777	18	
869	13.5	c
875	20	I
885	18	I
934	19	
945	20	

*Standard band magnitude designations. "c" indicates cross-calibration radiometer band

Table 3 (con't). Lunar Spectral Bandpasses

Possible SWIR Band Center Wavelengths (nm)	FWHM (nm)	Instrument Band
1240	20	MODIS 5
1450	50	Lunar ref. max.
1655	110	ASTER 4 & MODIS 5
1970	50	Lunar ref. min.
2130	50	MODIS 7
2260	40	ASTER 7
2385	70	ASTER 9

Table 4. Estimate of the Signal-to-Noise Factor for Lunar Irradiance Calibration

Definitions:

SNR ratio; the improvement in signal-to-noise ratio due to pixel aggregation, over that of a single pixel viewing a diffuse surface of albedo 0.1 with perpendicular solar incidence and no atmosphere.

This is modeled as $M^{1/2}$ x 10B x (N_1/N_2)

where:

- M = total number of pixels used = S x N_1
- N_1 = area of Moon, in units of pixel area ~ p x R_p^2
- N_2 = number of square pixels needed to sum all of lunar radiance ~ p x $(R_p + 1)^2$
- R_p = radius of the Moon in pixels
- S = “slowness” of imaging; the factor of how much more slowly the Moon is scanned than the nominal nadir scene angular velocity or how oblong the Moon appears in the image.
- B = effective albedo of the Moon
- Nominal EOS orbit height = 705 km
- Equivalent radius of the Moon = 3.188 km

Table 4. Estimate of the Signal-to-Noise Ratio for Lunar Irradiance Calibration (con't.)

______	MODIS & MISR			ASTER	
IFOV (km)	1	0.5	0.25	VNIR 0.015	SWIR 0.03
Lunar radius (pixels)	3.19	6.38	12.75	212.50	106.25
N_1	31.9	127.7	510.7	141863.1	35465.8
N_2	55.1	170.9	594.0	143201.4	36136.5
B	SNR Factors for S=1				
0.05	1.6	4.2	9.7	187	92
0.1	3.3	8.4	19.4	373	185
0.2	6.6	16.9	38.9	746	370
B	SNR Factors for S=10				
0.05	5.2	13.3	30.7	590	292
0.1	10.3	26.7	61.4	1180	584
0.2	20.7	53.4	122.9	2360	1169

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